Current offshore wind turbines are mostly derived from onshore designs with only minor adjustments. As offshore wind conditions differ from onshore applications, optimal future designs for large turbines will have to take integration issues into consideration.

Design criteria to be optimized are hub height, blade length and drive train power. Criteria for assessing the quality of a design are based on a multi-stakeholder-approach. Stakeholders are the investor, the grid operator, and the public.

The value for the investor is determined by the return on investment (ROI).

The value for the grid operator is determined by the Equivalent Load Carrying Capability (ELCC) and other similar methods (Equivalent Firm Capacity EFC, Equivalent Conventional Capacity ECC, Capacity Credit CC) that determine a wind power plants ability to contribute to the security of supply. A high CC reduces the number of backup power plants required, thus reducing grid operation costs.

Grid connection costs are considered as an indicator for the public value.

Based on an integrated tool for scaling, cost estimation, and simulation, the pareto-optimal designs for these criteria are derived.

Cost of Energy COE, Return on Investment ROI, and Capacity Credit CC for optimal designs are presented. A sensitivity analysis for main design drivers is conducted.

### Optimization Approach

The following design parameters for wind turbines have been identified as significant for energy yield, cost, and capacity credit:

1. The nominal power per rotor swept area, \( P_{s} \)
2. Nominal power of the drive train, \( P_{n} \)
3. Hub height, \( H \)
4. Distance from the coast, \( d \)
5. Water depth, \( T \)

This 5-dimensional “parameter space” is mapped to the three dimensional “quality space” using the quality function

\[ \text{ROI, COE, CC} = \text{qualityFunction}(P_{s}, P_{n}, H, d, T) \]

based on an empirical cost model [1], a Capacity Credit model [2] and a simplified economic model.

Starting at the edges of the hyperrectangle that forms the boundaries of parameter space, an iterative search algorithm tests points for pareto efficiency in quality space, as illustrated below.

### Cost Model and CC Model

The solver for the pareto efficiency problem, as well as the cost model and the model for the capacity credit are based on original research by the ‘Regenerative Energien’ research group at TU Darmstadt.

All models are implemented in Matlab® 2011a. The Matlab® object model was used to implement some of the more complex data structures.

The Pareto Efficiency Solver uses a ‘contract-expand’ strategy to generate suitable candidates for each iteration. Contracting is done by generating new candidates in the middle between ’known good’ points. While this strategy would be sufficient to find a solution that is convex in parameter space, it is insufficient for more complex problems. Thus, expansion is realized by generating new candidates also from already discarded points as well as by adding a ‘simulated annealing’ component to candidate generation.

Since the Capacity Credit Model from [1] is too slow for iterative parametric optimization, results from [2], [3] are used to generate lookup tables based on \( P_{s} \), capacity factor, location, and date. These are sufficiently fast and accurate for optimization.

The Empirical Cost Model from [1] was improved to better approximate the cost of wind turbines with very large rotor-swept-area to nominal-power ratios \( P_{s} \).

### Conclusions

As can be seen in figure 3, wind turbines with very high rotor-swept-area to nominal-power ratios \( P_{s} \) have high capacity credit caused by high capacity factors and are thus most desirable for grid operators.

An the other hand, the highest return-on-investment ROI and lowest cost-of-energy COE is achieved by turbines with lower CC (figure 1) and high nominal power (figure 4).

Figure 1 also illustrates, that the coastal-distance-dependent component of the German feed-in-tariff does not fully compensate the higher cost of installing wind turbines far from the coast. The same is the case for the depth compensation component.

The higher CC at the Baltic Sea site (FINO 2) as seen in figure 3 results from the different wind distribution at this site.

Figure 2 shows, that very large wind turbines can provide low COE and high ROI, but the use of smaller turbines can substantially increase the CC without significantly increasing the COE. Even a CC-compensation component to the feed-in-tariff might have a strong impact not only in reducing the need for stand-by power plants but also to reduce the cost for the grid connection.

### Assumptions

- **Operation and Maintenance:** 30% of FIT income
- **Interest Rate:** 7% p.a.
- **Operational lifetime:** 20 years
- **Reliability:** 95%
- **Wind turbine performance:** 85%